REMARKS

Claims 2-27, 29-43, and 45-58 are presently pending in this application and have been examined, and claims 3, 8-27, 30, 35, 36, 46, 47, and 49-58 are also pending but have been withdrawn from consideration as being drawn to a non-elected species. Claims 5, 32, and 45 have been rewritten in independent form to include all of the features of the corresponding base claim and any intervening claims. Claims 2-4, 6-10, 29-31, 33-36, 46, and 47 have been amended solely to change the dependencies of these claims. Claim 7 was further amended to improve the readability of this claim without changing the scope of the claim. Claims 1, 28, and 44 have been cancelled without commenting on or conceding the merits of the outstanding rejections. As such, these claims have been cancelled without prejudice to pursuing these claims in a continuation, divisional, or other application.

The status of the application in light of the Final Office Action dated September 23, 2004, is as follows:

(A) The Information Disclosure Statement filed March 3, 2003, was noted as failing to comply with 37 C.F.R. 1.98(a)(2);

(B) Claims 1, 2, 4, 28, 29, 31 and 44 were rejected under 35 U.S.C. § 103 over the combination of U.S. Patent No. 5,816,891 issued to ("Woo"), U.S. Patent No. 6,431,949 issued to Ishikawa et al. ("Ishikawa"), and U.S. Patent No. 6,340,327 issued to Afif ("Afif"); and

(C) Claims 37-43 and 48 have been allowed, and claims 5-7, 32-34 and 45 were indicated to be allowable if rewritten in independent form to include all of the features of their respective base claims and any intervening claims.

A. <u>Consideration of Information Disclosure Statement</u>

The references cited in the Information Disclosure Statement dated February 27, 2003 were not considered on the grounds that a legible copy of each U.S. and foreign patent, each publication or that portion which caused it to be listed, and all other information or that portion which caused it to be listed was not included with the IDS. In

a telephone conference with Mr. Steve Whelan on December 21, 2004, the Examiner acknowledged that copies of the U.S. patents are not required to be filed with the IDS and stated that the only copy needed is a copy of the single non-patent reference cited in the Information Disclosure Statement. The undersigned respectfully submits that a copy of this non-patent reference was sent to the U.S. Patent and Trademark Office with the IDS as noted in the previous response filed on 27 April 2004. The Examiner must, as a matter of the applicant's right, consider all of the references cited in the IDS because (a) copies of the U.S. patents are not necessary and (b) copies of all references were provided in the originally filed IDS. Moreover, even if the Examiner contends that copies of the references were not received by the United States Patent and Trademark Office, the U.S. patent references must be considered as a matter of right because copies of these references are not required. For the Examiner's convenience, another copy of the single non-patent reference cited in the Information Disclosure Statement is provided with this paper. The undersigned respectfully requests that the Examiner review the references cited in the Information Disclosure Statement and acknowledge his review in the record in accordance with the applicant's rights.

B. Response to the Section 103 Rejection

Claims 1, 2, 4, 28, 29, 31 and 44 were rejected under Section 103 over the combination of Woo, Ishikawa and Afif. Claims 1, 28, and 44 have been cancelled and, accordingly, the rejection of these claims is now moot.

As discussed below, base claims 5 and 32 are now allowable. Accordingly, claims 2, 4, 29, and 31 are allowable as depending from one of the allowable base claims 5 and 32, and also because of the additional features of these dependent claims. Therefore, the Section 103 rejection of claims 2, 4, 29, and 31 should be withdrawn.

C. Allowable Claims

The applicant thanks the claims for allowing claims 37-43, and indicating that claims 5-7, 32-34, and 45 would be allowable if rewritten in independent form to include all of the features of their respective base claims and any intervening claims. Claims 5,

32, and 45 have been rewritten in the stated form and, accordingly, the objection to these claims should be withdrawn.

Claims 6, 7, 33, and 34 are allowable as depending from one of the allowable base claims 5 and 32, and also because of the additional features of these dependent claims. Therefore, the objection to claims 6, 7, 33, and 34 should also be withdrawn.

Claims 5, 32, and 37 are generic to all of the withdrawn claims, and thus applicant requests reinstatement of claims 3, 8-27, 30, 35, 36, 46, 47, and 49-58 upon allowance of any one of generic claims 5, 32, and 37. Furthermore, the undersigned attorney notes that allowable claims 39, 42, and 43 have been rejoined in the application.

Conclusion

In view of the foregoing, the pending claims comply with 35 U.S.C. § 112 and are patentable over the applied art. The applicant respectfully requests reconsideration of the application and a mailing of a Notice of Allowance. If the Examiner has any questions or believes a telephone conference would expedite prosecution of this application, the Examiner is encouraged to call the undersigned at (206) 359-3982.

Respectfully submitted,
Perkins Coie LLP

Date: December 23, 2004

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l, 182 (1997).
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Brown, and R. C.
Kobayashi, W. Lin,
ciety Proceedings
and H. Mori, Jpn.

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Abrasive-Free Polishing for Copper Damascene Interconnection

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A complete abrasive-free process for fabricating copper damascene interconnection has been developed. The process is a combination of newly developed abrasive-free polishing (AFP) of Cu and dry etching of a barrier metal layer. A new aqueous chemical polishing solution and a polyurethane polishing pad produce complete stop-on-barrier characteristics of Cu polishing. The AFP provides a very clean, scratch-free, anticorrosive polished surface, and the total depth of erosion and dishing is reduced to less than one fifth of that produced by conventional slurries, even after 100% overpolishing. The barrier metal is successfully dry etched by using SF_6 gas at a high selectivity ratio (more than 10) of barrier metal to SiO_2. It was found that the developed AFP significantly reduces both Cu line resistance and its deviation. Moreover, AFP can also contribute to cost reduction of chemical mechanical polishing and help solve environmental problems related to waste slurries.

Manuscript submitted March 27, 2000; revised manuscript received June 27, 2000.

The copper damascene process is one of the most promising technologies to fabricate Cu interconnection for high-speed logic LSIs (large-scale integrated circuits).[1,2] Chemical mechanical polishing (CMP) of Cu and barrier metals is one of the most important techniques for fabricating Cu damascene interconnects. Since conventional CMP slurries contain alumina abrasives, which are mechanically very hard, many scratches are generated not only on Cu but also on a SiO_2 film surface. The SiO_2 surface damage produced after CMP of the barrier metal degrades dielectric breakdown reliability.

SiO_2 erosion and Cu dishing have been also serious problems, especially in the area of high pattern density.[3] This erosion is defined as oxide loss around the patterned Cu area and dishing is defined as Cu thickness loss inside the Cu pattern. Erosion and dishing degrade the interconnect planarity and make it difficult to fabricate high-density multilevel interconnects at a high yield.[4] To minimize thickness loss, a slurryless polishing, which is a combination of a fixed abrasive pad and aqueous chemical solution, has been developed.[5] However, defectivity and post-CMP cleaning are still problems with this method.[6]

Post-CMP cleaning technologies to remove abrasive particles on polished wafers have been developed. For example, PVA (polyvinyl alcohol) sponge-brush cleaning and megasonic cleaning have been used with chemical additives.[7,8] Since these additives often produce Cu surface damage, electrolyzed waters (anode water and cathode water) have been proposed.[9] These cleaning systems, however, raise the total cost of the CMP process.

Although a CMP machine uses large amounts of slurry, which generates particles (abrasives), it must be operated in a clean room. These particles decrease chip yield in the metallization process. To suppress the particles, a special room must be set up for CMP machines in order to maintain the degree of cleanliness.

As explained previously, the metal CMP process has many problems that must be solved. It is obvious that these problems originate from abrasives included in the slurry, but the solid abrasives have been previously thought indispensable in order to increase removal rate of the metal. In polishing without abrasives, the removal rate was quite low (less than 10 nm/min); thus, abrasive-free polishing could not be put to practical use. Accordingly, we have developed a complete abrasive-free process for Cu damascene interconnection by using a combination of new Cu-AFP (abrasive-free polishing) and barrier-metal dry etching.[10]

Experimental

AFP conditions.—The new polishing solution comprises only chemical agents such as oxidizer, etchant, and corrosion inhibitor, but it does not contain abrasives. It is, therefore, transparent shown in Fig. 1a. In this experiment, the oxidizer was mixed with t other agent just before polishing in order to suppress the decomp sition of the oxidizer. We used hydrogen peroxide aqueous soluti (30 wt %) as the oxidizer. A popular, commercially available, a mina-abrasive-type CMP slurry for polishing Cu was also evalua for comparison (Fig. 1b). The size of the abrasives (3.5 wt %) about 230 nm and pH of the slurry is about 3.8.

A CMP machine (Lapmaster SFT, LGP-552XJ-2) with two 24 diam platens was used. A foamed-polyurethane-type, hard polish pad (Rodel, IC1000) was used as a standard pad. A lattice gro (XY groove) with a 15 mm pitch was formed (Rodel, A21 type) concentric-circle groove (K groove) pad, a stacked pad (Ro IC1400), a softer pad (Rodel, XHGM1158), a harder pad (Univer ESM-S), and a fixed abrasive pad (Universal, LP99) were also u for comparison. *Ex situ* pad dressing was carried out using an a proof diamond dresser. The distance between the center of the p en and the center of the wafer holder is 150 mm.

The down force was varied from 5 to 40 kPa (50-400 g/cm^2) the standard force for polishing patterned wafers was 22 kPa. platen speed was varied from 15 to 60 rpm and the standard s was 30 rpm. The AFP solution was supplied onto the polishing at a flow rate of 200 mL/min.

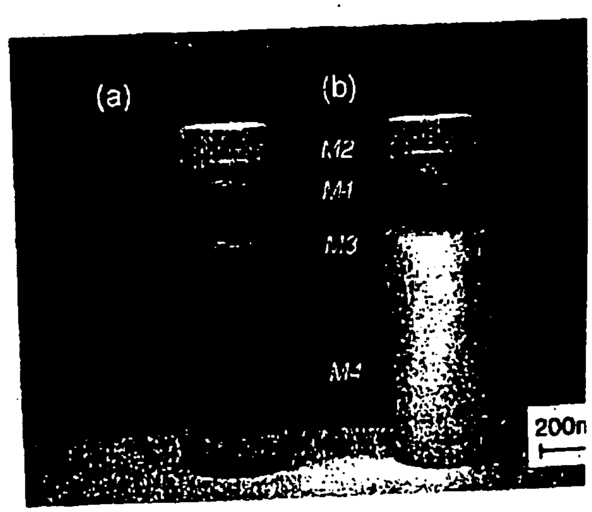

Figure 1. Comparison of (a) the new AFP solution and (b) a conve alumina slurry. The picture behind is a bird's eye view of multilevel C connection fabricated by AFP.

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Sample preparation.—The Cu lines were formed on 8 in. wafers with interconnect patterns, *i.e.*, test element groups (TEG). The Cu film was deposited by long-throw sputtering and was filled by heat-treatment of 430°C for 3 min. TiN or TaN was used as a barrier metal.

The removal rate of Cu was evaluated by polishing a Cu-deposited wafer (800 nm thick, no pattern) for 2 min and measuring change in sheet resistance at 49 points on the wafer before and after the polishing. The sheet resistance was measured by four-point probe (Resistivity Test System, Kokusai Electric, VR-70), and within-wafer nonuniformity (WIWNU) of the removal rate was evaluated by the equation, (max − min)/(max + min) (±%), where "max" and "min" mean the maximum and minimum removal rate at the 49 points. Wafer edge exclusion of the measurement was 10 mm.

The etching rate of Cu was evaluated by measuring the change in Cu sheet resistance before and after 10 min etching in the polishing solution. The sample was a sputter-deposited Cu film (200 nm thick) on a Si chip (15 × 15 mm size) with an adhesion layer of TiN (50 nm thick), and the sheet resistance was measured at the center of the chip by four-point probe (Napson, RG-7).

The amounts of erosion and dishing were evaluated by using a stylus scanner (Tokyo Seimitsu, Surfcom 570-3DF) and SEM (scanning electron microscope, Hitachi S-900). We used these techniques to measure the line-array pattern formed at a pitch from 800 nm to 200 μm. The line-array pattern is 1 × 3 mm. The largest Cu area without SiO_2 pillars in the TEG is 3 × 3 mm. The dishing depth of this area was apparent (without the need for SEM) just after CMP when the dishing depth exceeds a line depth of 500 nm.

Dry etching of the barrier metal was carried out by ICP (inductively coupled plasma) reactive-ion etching (RIE, Surface Technology Systems). A SF_6 gas was used as the process gas. The gas flow rate and the plasma pressure was 25 mL/min and 0.67 Pa, respectively. The radio frequency (rf) power was 600 W (13.56 MHz) and bias power was varied from 0 to 100 W. The dry etching rate dependence on the bias power was examined using samples of TiN, TaN, SiO_2, and Cu. The etching rates of the three metals were evaluated by measuring the sheet resistance as explained previously, and that of SiO_2 was evaluated by measuring the thickness change by ellipsometer.

Results and Discussion

AFP mechanism.—A model of tungsten-CMP, *i.e.*, a combination of film-surface oxidation and the mechanical abrasion by alumina abrasives, has been proposed by Kaufman *et al.*[11] Conventional slurries for metal CMP mainly comprise oxidizers, such as hydrogen peroxide or ferric nitrate, and abrasives such as alumina particles or silica particles. A small amount of organic acid is added in order to raise the removal rate of metal over that of SiO_2.[12] Most commonly, CMP is performed on a foamed polyurethane polishing pad, and the removal rates of 100-500 nm/min are attained under ordinary polishing conditions (down force of about 30 kPa and platen speed of about 40 rpm).

Since Cu is chemically active, we tried to planarize Cu by "soft friction" using the foamed polyurethane pad rather than by abrasion with "hard" abrasives. The new AFP solution basically comprises three chemicals: an oxidizer, an etchant, and a corrosion inhibitor.

We suggest the mechanism of AFP is as follows. The Cu surface is oxidized by the oxidizer, and the thin oxide film is protected by the inhibitor as shown in Fig. 2a. Then the protection layer on the protruded regions is removed by "soft friction" with the polishing pad, and the oxide is dissolved by the etchant (Fig. 2b). The exposed Cu surface on the protruded regions is oxidized and etched again, while the recessed regions remain protected by the inhibitor. Then the Cu surface is planarized and AFP automatically stops on the barrier metal (Fig. 2c). Because the barrier metal is hardly removed without abrasives, erosion would not occur even when a long over-polishing is carried out. Finally, the barrier metal is removed by barrier-metal-selective CMP or dry etching (Fig. 2d).

The most important point of AFP is the quality of the protection layer. If the protection layer is too strong, it is hardly removed by the "soft friction" of the polyurethane pad and the removal rate would be

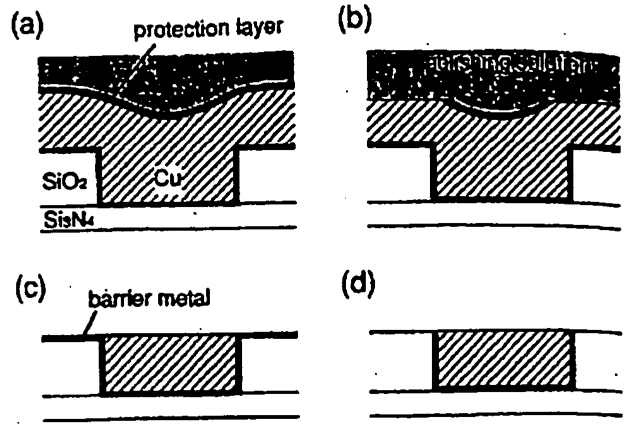

Figure 2. Mechanism of Cu AFP: (a) formation of protection layer, (b) abra sion of protruded area, (c) polishing stop on barrier metal layer, and (d removal of barrier metal layer.

slow. If the protection layer is too weak against the etchant, th removal rate would be fast; however, Cu dishing or corrosion woul occur. Thus, the protection layer should be soft enough to be re moved by the polyurethane pad during polishing but strong enoug to protect the recessed area of Cu from the etchant. In other words the polishing solution should be corrosive enough to raise the re moval rate to more than 100 nm/min but passivative enough to re duce the Cu dishing to less than 50 nm.

To evaluate the performance of the polishing solution, we use the ratio of the removal rate and etching rate (rate ratio) as an inde to optimize the formulation of polishing solution. The Cu etchin rate indicates the strength of the protection layer against the etchan and Cu dishing can be suppressed as much as possible by reducin the etching rate to less than 1 nm/min, but the required removal rat is more than 100 nm/min. The developed polishing solution, there fore, has the rate ratio of more than 100.

Removal rate of Cu AFP.—Removal rate of Cu by the AFP solu tion is plotted in Fig. 3. The platen speed was fixed at 30 rpm in thi polishing experiment. Practically applicable removal rates, as hig as 100-180 nm/min, and WIWNU of less than ±12% was attained more than 10 kPa. Unlike the conventional alumina slurry whic shows a linear trend, the removal rate saturates at around 200 nm min when the down force increases more than 20 kPa.

Dependence of the Cu removal rate on the platen rotational spee is shown in Fig. 4. The down force was fixed at 22 kPa in this po

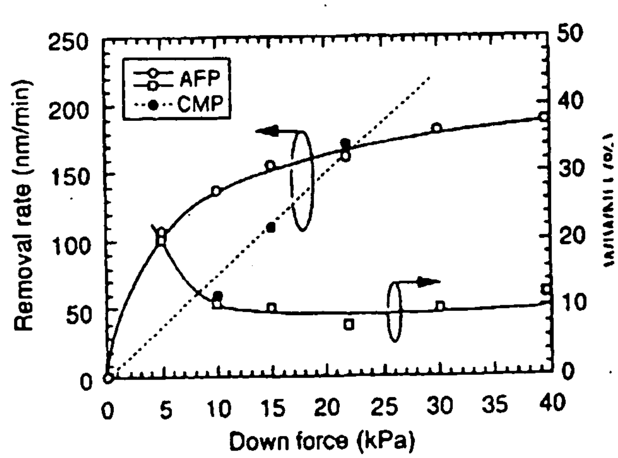

Figure 3. Dependence of Cu removal rate and WIWNU on down force AFP. Removal rate of conventional CMP is also shown as a dotted line f comparison. Platen rotational speed is fixed at 30 rpm.

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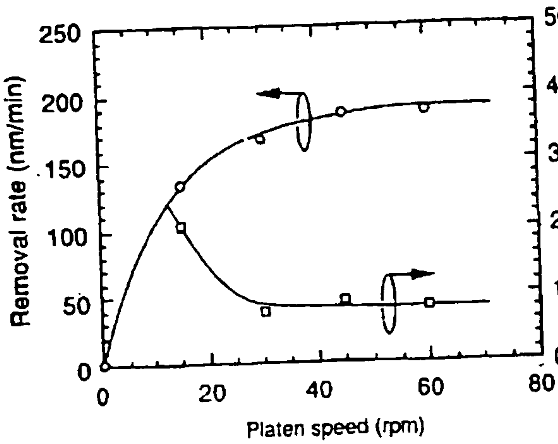

Figure 4. Dependence of Cu removal rate and WIWNU on platen rotational speed in AFP. Down force is fixed at 22 kPa.

ishing experiment. WIWNU of less than ±10% was attained at more than 30 rpm. This figure also shows a saturation tendency at around 200 nm/min when the platen speed exceeds 45 rpm. These two saturation tendencies are very different from the line given by Preston's equation.[13] This difference is attributed to the fact that the chemical effect is dominant over the mechanical effect in our AFP.

Next, we compared the Cu removal rate depending on polishing pads (Fig. 5). A difference of groove type (XY groove or K groove) does not affect the Cu removal rate; however, WIWNU was found to be better when an XY-groove pad (±5.8%) was used rather than a K-groove pad (±25%). This is thought to be because the polishing solution can flow smoothly in the radial direction of the XY groove rather than the concentric direction of the K groove. Single-layered (IC1000) and stacked pads (IC1400) have almost equal removal rates and uniformities. A softer pad, XHGM1158, has a very low removal rate of 15 nm/min, and a harder pad, ESM-S, has an almost equal removal rate to that of IC1000 because the softer pad is too tender to remove the protection layer formed by the polishing solution and because the removal rate saturates once the hardness of the pad exceeds a certain value. This removal rate saturation seems to be the same as the saturation tendency shown in Fig. 3. The removal rate exceeds 200 nm/min when a fixed abrasive pad (LP99) is used; however, this pad suffers problems of erosion and scratching.

Though it may seem that these removal rates are quite low compared with those of conventional alumina slurries, anticorrosive characteristics of this AFP solution are much better than those of conventional slurries. The etching rates of commercially available conventional slurries are usually 2-20 nm/min,[14] while that of ou[r] AFP solution is suppressed down to about 0.2 nm/min. This difference in etching rate results in the difference in the removal rates o[f] AFP and CMP. As long as we use conventional abrasive slurries high etching rate does not seem a serious problem because the C[u] dishing or the surface corrosion disappear due to oxide erosion. Thi[s] was confirmed by adding abrasives into the AFP solution.[15] Th[e] dishing and erosion are interdependent (*e.g.*, faster dishing leads t[o] faster erosion) and depend strongly on linewidth and line space. O[n] the other hand, in AFP, etching rate should be suppressed down t[o] the erosion formation speed (that is, negligible), otherwise the C[u] surface is etched (etching rather than dishing) and step is formed a[t] the interface between the Cu surface and the SiO_2 surface. The dish[-] ing occurs independently of erosion, and the erosion is not enhance[d] by the dishing at any linewidth or line space.

Since the AFP removal rates of barrier metals are quite low, *e.g.* less than 10 nm/min for TiN, the Cu AFP stops automatically whe[n] the barrier layer is exposed. Figure 6 shows an AFP stop on TiN fil[m] in the area of high pattern density (800 nm pitch line array, 30% ove[r-] polish time). A very smooth, scratch-free Cu surface is obtained prob[-] ably because of "soft" friction. Stop-on-barrier characteristics (f[or] two-step or multistep CMP of a TaN barrier film) were reported,[16] b[ut] TiN stop has been difficult, especially after overpolishing, becau[se] TiN was easily removed during the abrasive Cu-CMP. AFP enabl[es] TiN was easily removed during the abrasive Cu-CMP. AFP enabl[ed] complete stop-on-barrier characteristics using both TiN and TaN.

Evaluation of erosion and dishing.—The advantage of AFP co[m-] pared with conventional CMP becomes evident when overpolishi[ng] is performed. The overpolish time is defined as the time after e[nd] point is detected in the CMP machine. Figure 7 compares overp[ol-] ishing by AFP with that by one-step CMP using conventional al[u-] mina slurry. It is clear from this figure that AFP hardly removes t[he] SiO_2 layer up to 100% overpolish (two times longer than just p[ol-] ishing) even in the area of high pattern density (800 nm pitch li[ne] array pattern). The amounts of erosion and dishing in the same a[rea] as that in Fig. 7 were and are shown in Fig. 8. The erosion by A[FP] is not enhanced even on the 100% overpolishing stage. Howev[er,] since a Cu line is 500 nm deep, erosion by conventional CMP [in-] creases up to 270 nm and more than half of the Cu is polished [off] after 100% overpolishing. This large erosion is shown in the SE[M] image of Fig. 7f.

The amounts of dishing in the area of wide Cu lines (50 μm li[nes] and 100 μm lines) were evaluated using the stylus scanner (Fig.

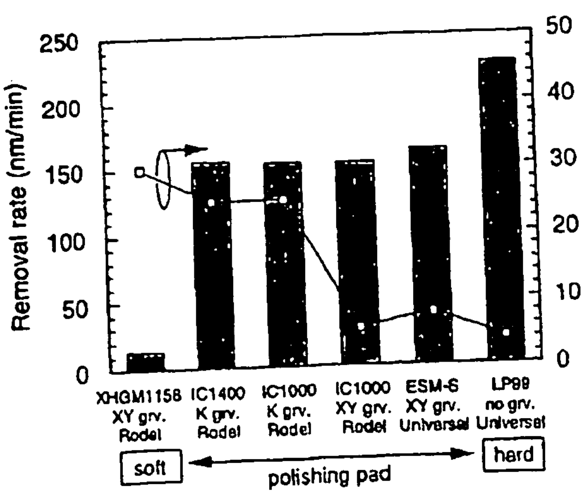

Figure 5. Dependence of Cu removal rate and WIWNU on type of polishing pad.

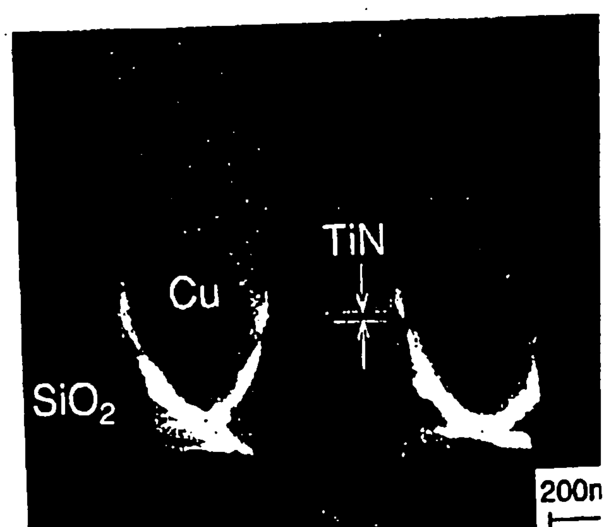

Figure 6. Cross section of Cu line array after AFP (barrier metal remains).

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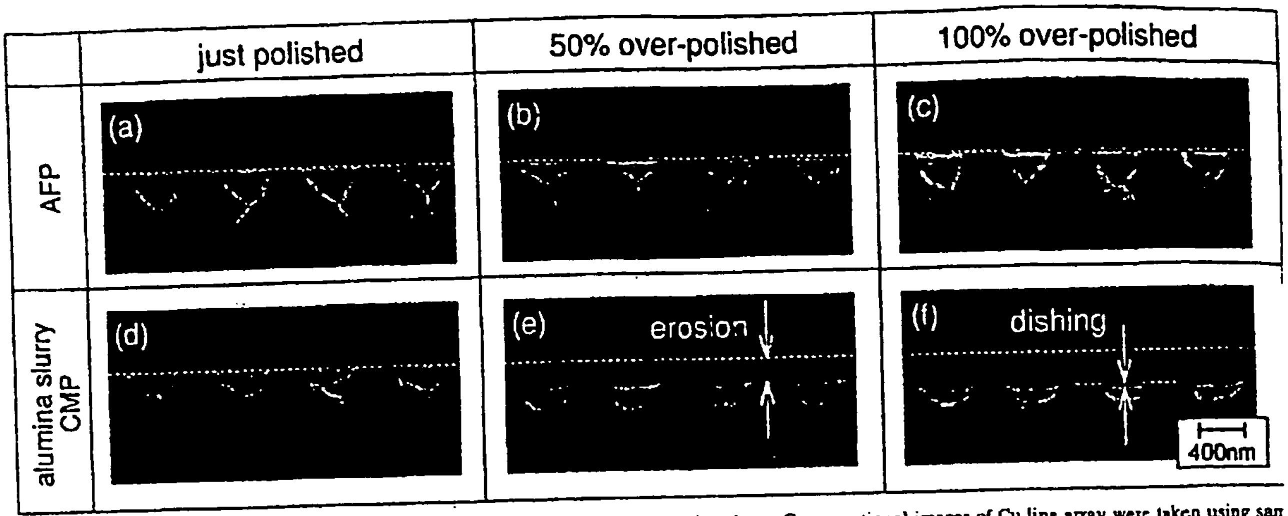

Figure 7. Erosion depth by AFP compared to that by conventional CMP using alumina slurry. Cross-sectional images of Cu line array were taken using sam ples of just polished, 50% overpolished, and 100% overpolished.

The dishing depth of the 100 μm wide lines is more than 400 nm when CMP is performed up to 100% overpolishing. Because the erosion depth of this area was more than 100 nm, Cu did not remain in the center of the SiO_2 groove (interconnect area). This was confirmed by optical microscope (Fig. 10a). On the other band, the dishing depth of this area formed by AFP is suppressed below 80 nm even on the 100% overpolishing stage, and the whole Cu area remains as shown in Fig. 10b. The largest Cu area in our TEG (3 × 3 mm Cu pad without SiO_2 pillars) is also formed without missing the Cu inside the pattern.

As is well known, WIWNU of deposition thickness by Cu electroplating is inferior to that by sputtering deposition because the electroplating is sensitive to the electrical contact of the electrode. If WIWNU of deposition thickness is assumed to be ±20%, more than 40% overpolishing must be performed: erosion is enhanced in the thin deposited area where the overpolishing is fully performed. This degradation of planarization would be recovered at the end of the Cu-AFP because AFP stops on the barrier metal film as shown in Fig. 7.

AFP technology becomes more important when we fabricate multilevel damascene metallization. Figure 11a points out a problem of erosion and dishing using conventional slurry.[4] The eroded surface line of the first-level (a1) is traced to the surface lines of the second-level SiO_2 film (a2) and also Cu film (a3). When the seconc level CMP is performed, Cu residue remains in this eroded area (a4 A typical Cu residue is shown in Fig. 12. To remove this Cu residu overpolishing must be carried out and second-level erosion is e hanced as shown in Fig. 11 (a5). This degradation of planarizatic makes it difficult to fabricate a multilevel metallization. In contras AFP produces a realistic multilevel metallization structure as show in Fig. 11b. A short circuit due to Cu residue is avoided and, mo importantly, Cu interconnects can be fabricated to the design siz Consequently, AFP has been successfully applied to fabricating C multilevel interconnects.[2]

Dry etching of barrier metals.—The barrier metals can be r moved by barrier-metal-selective CMP.[17] In order to eliminate abr sives in the process, we tried to develop barrier-metal AFP. Howe er, barrier metals such as TiN and TaN are considerably inert chemicals in comparison with Cu. When a strong etchant is use high polishing selectivities of the barrier metals to Cu and to Si cannot be attained.

In the current work we used RIE with SF_6 gas which hardly etc es Cu. This dry etching removes the barrier layer stably without cau ing Cu corrosion. Figure 13 shows the dependence of etching rate TiN and SiO_2 on bias power. The etching rate of Cu was negligit

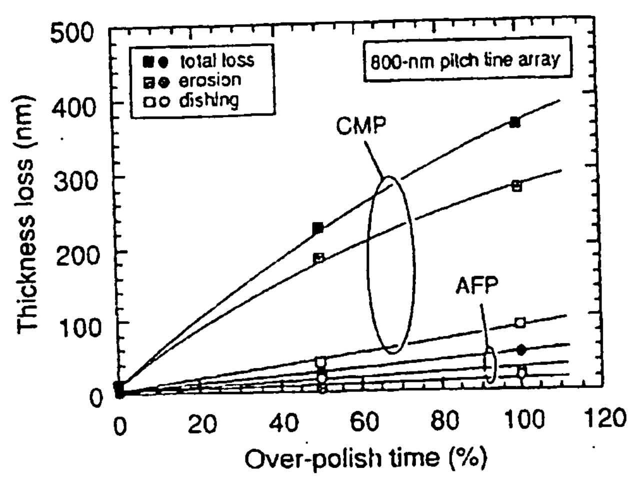

Figure 8. Dependence of erosion and dishing depth on overpolish time of AFP and conventional CMP in the narrow Cu line array area.

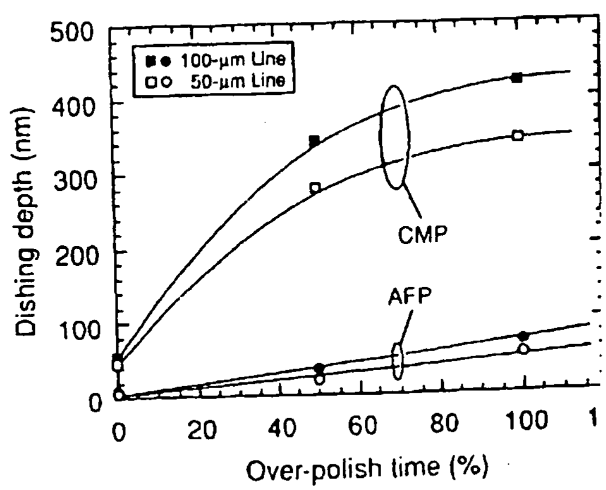

Figure 9. Dependence of dishing depth on overpolish time of AFP and conventional CMP in the wide Cu line array area

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small. The etching selectivity of TiN to SiO_2 is also shown in the figure. It is clear that the selectivity is a maximum at zero bias power, so we used this power in order to etch the barrier metal after AFP and, consequently, successfully fabricated damascene interconnects. Table I compares the etching rate and selectivities to SiO_2 of TiN and TaN.

Advantages of AFP.—AFP has several advantages. First, it produces low electrical resistance. The reduction in thickness loss (both erosion and dishing) directly affects the reduction in electrical resistance of the Cu interconnects. AFP clearly decreases the resistance of the Cu lines by about 15%; more important, the resistance deviation is reduced to less than half that obtained by conventional CMP (Fig. 14). The deviation of 15% is attributable to the SiO_2 dry-etching process because the end point of Cu AFP is almost perfect (as shown in Fig. 6), and erosion after the barrier metal removal is less than 15% of the total thickness of Cu interconnect (500 nm).

Second, by using AFP, we do not have to use a complicated post-CMP cleaning technology, such as an electrolyzed water system[9] or

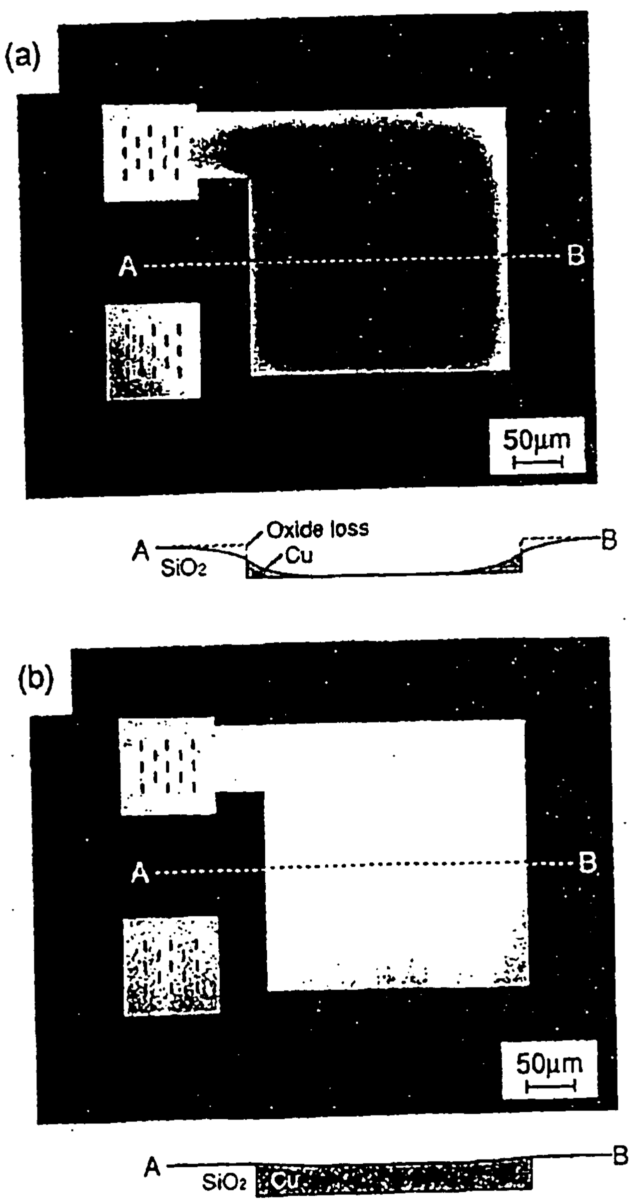

Figure 10. (a) A large Cu dishing by conventional CMP and (b) an improved polished Cu surface by AFP. Cross sections of the polished surface are also illustrated.

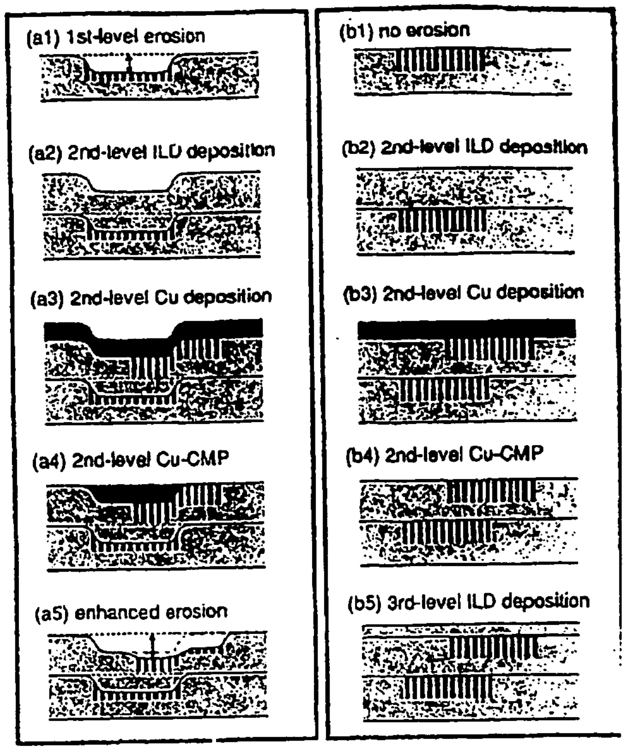

Figure 11. (a) Multilevel damascene metallization by conventional CMP an (b) by AFP.

developed cleaning chemicals, to remove abrasives. As shown i Fig. 6, the polished surface by AFP is easily cleaned by only wate brush scrubbing without chemical additions. To clean metal contam ination, which degrades dielectric-breakdown reliability, conver tional chemicals such as organic acids might be enough.

The third advantage is low damage during polishing. Hard abra sives in the slurry cause scratches not only on a Cu surface but als on a SiO_2 surface, and open/short circuit failures occur. The chi yields have been more than doubled by using AFP on our productio line. Moreover, reduction in shallow-defect damage improved diele tric breakdown reliability.[18] Since many low-*k* materials have lowe mechanical strength than SiO_2,[19] surface damage is easily produce by hard abrasives and AFP will be indispensable in the next-genera tion low-*k*/Cu damascene process.

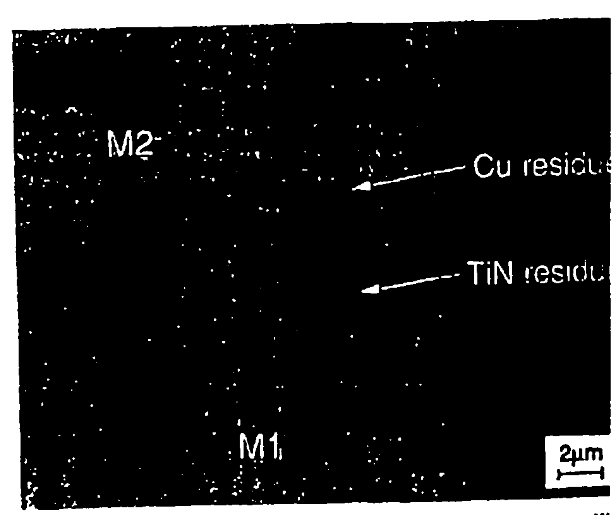

Figure 12. Cu residue in the eroded area of the second-level Cu metalli tion.

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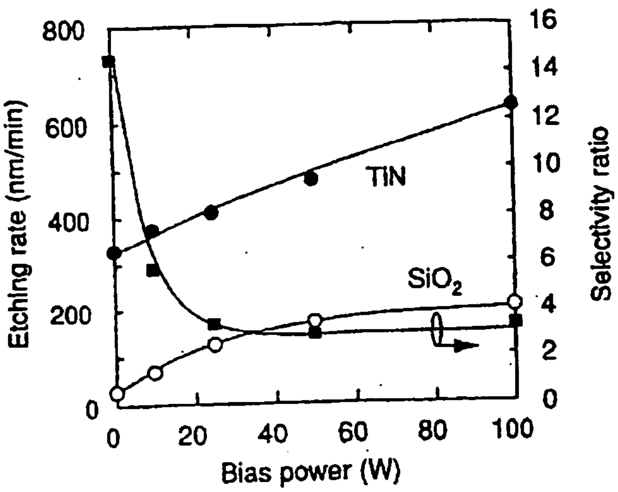

Figure 13. Dry etching rate of TiN and SiO_2. Etching selectivity ratio of TiN to SiO_2 is also shown.

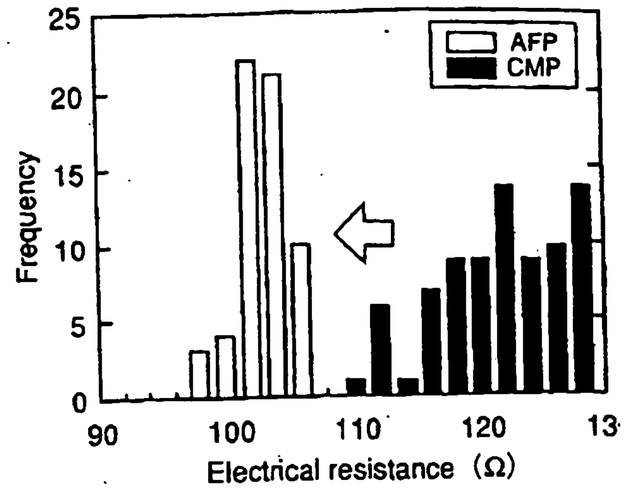

Figure 14. Comparison of electrical resistance of Cu test patterns made l AFP and conventional CMP.

The fourth advantage is a possible cost reduction. The total cost of the Cu CMP process is known to be much higher than that of other metallization processes. Especially, the cost of consumable materials such as slurry and polishing pads accounts for more than half of the total CMP cost. AFP can reduce slurry cost considerably because most of this cost is related to the abrasive technology such as synthesizing, dispersion, and quality control. If the total cost of the CMP process is reduced, the Cu damascene process can be applied to the metallization of dynamic random access memories (DRAMs), so AFP technology will be spread worldwide.

Fifth, the particle problem in a clean room might be solved by using AFP technology. Without abrasive, a CMP machine can be treated as a usual wet station in a clean room; thus, we do not have to set up a special room for CMP machines in order to maintain the degree of cleanliness. This advantage also contributes to the cost reduction of the CMP process and increases the yields of chips in the metallization process.

The environmental problem of waste CMP slurries has become a subject of critical concern. Previously, a disposal system for waste CMP slurries has been required, but it is also costly. Especially, alumina abrasive is chemically more stable than silica abrasive, so special chemicals are necessary for dealing with these waste abrasives. In contrast, waste AFP solution can be neutralized and mixed with the other aqueous solutions after the cleaning process. If other abrasive-free slurries, such as those in W-CMP and dielectric CMP, are also developed, semiconductor plants do not have to maintain a slurry-disposal system. This is yet another advantage of AFP.

Conclusions

A complete abrasive-free process for Cu damascene metallization was developed. In this process, AFP of Cu in conjunction with barrier-metal dry etching provides a very clean, scratch-free, anticorrosive, polished Cu surface. This combination of processes can reduce the total depth of erosion and dishing of both dense-line areas and wide-line areas to less than 50 nm after the usual overpolish time (50%). The process greatly improves both the yields and performance of the Cu-interconnect fabrication process. This so-called low-damage AFP will be indispensable in the next-generation lo' k/Cu damascene processes. Moreover, it will also contribute to cc reduction of CMP and help solve environmental problems associ ed with waste slurries.

Table I. Dry etching rate and selectivity ratio, etching rate of TiN (TaN) to etching rate of SiO_2.

	TiN	TaN	Cu
Etching rate (nm/min)	320	240	<1.0
Selectivity to SiO_2	15	11	—

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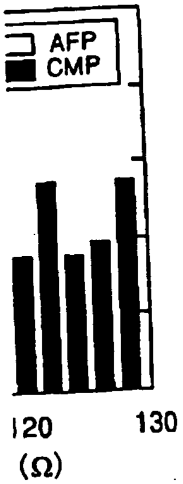
References

1. D. Edelstein, J. Heidenreich, R. Goldblatt, W. Cote, C. Uzoh, N. Lustig, P. Ro T. McDevitt, W. Mostiff, A. Simon, J. Dukovic, R. Wachnik, H. Rathore, Schultz, L. Su, S. Luce, and J. Slattery, in *Proceedings of International Elec Devices Meeting (IEDM)*, p. 773, Washington, DC (1997).
2. T. Hashimoto, T. Kikuchi, K. Watanabe, N. Ohashi, T. Saito, H. Yamaguchi Wada, N. Natsuaki, Y. Kondo, S. Kondo, Y. Homma, N. Owada, and T. Ikedi *Proceedings of International Electron Devices Meeting (IEDM)*, No. 8-4, Francisco, CA (1998).
3. J. Steigerwald, R. Zirpoli, S. Murarka, D. Price, and R. Gutmann, *J. Electrocl Soc.*, 141, 2842 (1994).
4. T. Park, T. Tugbawa, D. Boning, S. Hymes, T. Brown, K. Smekalin, anc Schwartz, in *Chemical Mechanical Polishing in IC Device Manufacturing* R. L. Opila, C. Reidsema Simpson, K. B. Sundaram, I. Ali, Y. A. Arimoto, Y. Homma, Editors, PV 99-37, p. 94, The Electrochemical Society Proceed Series, Pennington, NJ (1999).
5. M. Fayolle, J. Lugaud, F. Weimar, and W. Broxvoort, in *Proceedings of Ch cal-Mechanical Planarization for ULSI Multilevel Interconnection Confer (CMP-MIC)*, p. 128, Santa Clara, CA (1998).
6. K. Mikhaylish and M. Ravkin, in *Proceedings of Chemical-Mechanical Plana tion for ULSI Multilevel Interconnection Conference (CMP-MIC)*, p. 337, S Clara (2000).
7. S. Ray, I. Ali, G. Shinn, N. Furusawa, R. Shah, S. Peterman, K. Witt, S. East and P. Kumar, *J. Electrochem. Soc.*, 142, 216 (1995).
8. J. Larios, M. Ravkin, D. Hetherington, and J. Doyle, *Semicond. Int.*, 121 (1996).
9. H. Aoki, M. Monta, and M. Tsuji, U.S. Pat. 5,676,760 (1997).
10. S. Kondo, N. Sakuma, Y. Homma, Y. Goto, N. Ohashi, H. Yamaguchi, an Owada, in *Proceedings of the International Interconnect Technology Confe. (IITC)*, San Francisco, p. 253 (2000).
11. F. Kaufman, D. Thompson, R. Broadie, M. Jaso, W. Guthrie, D. Pearson, an Small, *J. Electrochem. Soc.*, 138, 3460 (1991).
12. G. Brancaleoni and L. Cook, U.S. Pat. 5,391,258 (1995).
13. F. Preston, *J. Soc. Glass Technol.*, 11, 214 (1927).
14. Y. Homma, S. Kondo, N. Sakuma, K. Hinode, J. Noguchi, N. Ohashi, H. aguchi, and N. Owada, *J. Electrochem. Soc.*, 147, 1193 (2000).
15. S. Kondo, N. Sakuma, Y. Homma, and N. Ohashi, in *Electrochemical Proc in ULSI Fabrication I and Interconnect and Contact Metallization: Materials*



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... Proceedings of Chemi-
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Journal of The Electrochemical Society, 147 3907-3913 (2000)
S0013-4651(00)03-118-9 CCC: $7.00 © The Electrochemical Society, Inc.

cesses, and Reliability, P. C. Andricacos, J. O. Dukovic, G. S. Mathad, G. M. Oleszek, H. S. Rathore, and C. Reidsema Simpson, Editors, PV 98-6, p. 195, The Electrochemical Society Proceedings Series, Pennington, NJ (1998).

16. S. Wang, V. Brusic, J. Hawkins, I. Cherian, L. Knowles, C. Schmidt, B. Cruz, K. Miller, D. Garcia, H. Chou, C. Baker, G. Grover, and C. Yu, in *Proceedings of Chemical-Mechanical Planarization for ULSI Multilevel Interconnection Conference, CMP-MIC Conference*, p. 477, Santa Clara, CA (2000).
17. H. Yamaguchi, N. Ohashi, T. Imai, K. Torii, J. Noguchi, T. Fujiwara, T. Saito, N. Owada, Y. Homma, S. Kondo, and K. Hinode, in *Proceedings of the Intern... Interconnect Technology Conference (IITC)*, San Francisco, CA, p. 264 (20...
18. J. Noguchi, N. Ohashi, J. Yasuda, T. Jimbo, H. Yamaguchi, N. Owada, K. T... and K. Hinode, in *Proceedings of the 38th Annual International Reliability ... Symposium (IRPS)*, San Jose, CA, p. 339 (2000).
19. T. Furusawa, N. Sakuma, D. Ryuzaki, S. Kondo, K. Takeda, S. Machida, ... Hinode, in *Proceedings of the International Interconnect Technology Con... (IITC)*, San Francisco, CA, p. 222 (2000).